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Telecommunications and Navigation Strategies for Mars Exploration

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Abstract

We examine, from a multimission program perspective, key issues and recommended strategies for three aspects of telecommunications and navigation support to future Mars exploration missions. First, we address the challenge of ensuring high-rate, robust telemetry during critical mission events, such as Mars Orbit Insertion, Entry/Descent/Landing, or Mars Ascent Vehicle launch. Obtaining real-time telemetry during such critical mission events, with the bandwidth required to characterize engineering system performance, will provide the program with needed feed-forward information in the event of an anomaly. In addition to quantifying supportable data rates, we will address the mission design issues involved in ensuring communications link availability to an on-orbit relay spacecraft at the epoch of the critical event. Second, we discuss the longer-term telecommunications support of surface assets over their mission lifetimes. The anticipated Mars mission set includes a diverse set of *in situ* spacecraft, ranging from large, highly mobile rovers with considerable landed mass and power, to small, extremely energy-constrained scout-class missions with little or no direct-to-Earth communications link capability. Telecommunications performance will be quantified for a variety of relay orbit options in terms of such key figures of merit as data return, link availability, and link energy efficiency. Third, we examine the potential for extracting navigation information from these *in situ* radio links. Specifically, we quantify the navigation accuracies that can be achieved for such program mission scenarios as approach navigation (for aerocapture or precision landing), surface position determination (for highly mobile rovers), and orbit determination (for support of on-orbit rendezvous with an orbiting sample canister).

Introduction

Mars has emerged as a focal point of planetary exploration. An international ensemble of missions is planned over the coming decade, with spacecraft contributed by NASA, ESA, CNES, ASI, and NASDA. The proposed mission sequence embodies a systematic approach to answering fundamental questions about the Martian environment and, in particular, the possibility that Mars has been an abode for past or present life.

Figure 1 illustrates the currently planned program of Mars exploration missions. Key aspects of the program include:

- A sequence of remote sensing science orbiters, including NASA Mars Odyssey (2001), ESA Mars Express (2003), NASA Mars Reconnaissance Orbiter (2005), and ASI/NASA Synthetic Aperture Radar Orbiter (2009). (The CNES Premier Orbiter (2007), which will deploy the four Netlanders and demonstrate aerocapture and on-orbit rendezvous techniques, may also carry out a remote sensing mission; its full science mission has not yet been selected at this time.)
- A parallel sequence of landers, including small "scout-class" landers such as the ESA Beagle 2 (2003) and the four CNES Netlanders (2007), medium-sized lander/rovers like the NASA Mars Exploration Rovers (2003), and large landers like the NASA Smart Lander (2007) with a second-generation Entry, Descent, and Landing capability incorporating aeromaneuvering and active hazard avoidance.
- A Sample Return mission currently slated for 2011, returning 500 g of scientifically-selected surface, sub-surface, and atmospheric samples to Earth, leveraging technologies demonstrated in the earlier 2007 Smart Lander and Premier Orbiter missions.
- Competitively-selected scout-class missions in the 2007 and 2011 opportunities.
- The first dedicated Mars telecommunications satellite, the ASI/NASA G. Marconi mission, in 2007.

A detailed list of current and planned Mars missions, with a listing of their key telecommunications parameters, is included in the Appendix.

This mission set poses a number of driving telecommunications and navigation challenges. First is the need for critical event communications. With the loss of the 1998 Mars Polar Lander, which failed during descent and with no active communications at the time of the anomaly, a policy was established to ensure capture of feed-forward engineering telemetry whenever possible during critical mission events, in order to understand and learn from any future mission anomalies. Examples of critical events include Entry, Descent, and Landing (EDL), Mars Orbit Insertion (especially for aerocapture MOI events), or the launch of a Mars Ascent Vehicle. Data rate requirements for critical event communications are highly dependent on the nature of the flight systems which need to be characterized. For instance, the simple ballistic EDL sequence utilized by the MER landers can be well-characterized (and diagnosed in the event of an anomaly) by a relatively small data volume. On the other hand, the active guidance loops involved in the Smart Lander aeromaneuvering and hazard avoidance will demand orders-of-magnitude larger data rates to capture sufficient engineering telemetry to characterize the performance of these systems.

Once landed assets reach the surface, a second challenge is the need for increased telecommunications support. There are two aspects to this challenge. First, the steady increase in spatial and spectral resolution of planned science instruments on both the orbiting and surface spacecraft will demand significant increases in returned data volume. The three-fold improvement in linear angular resolution of the MER Panoramic Camera (PANCAM), relative to the Mars Pathfinder PANCAM, increases by an order of magnitude the data volume of each panoramic image. Future hyperspectral imagers will further drive data volume. Increased mobility of future rovers will also naturally drive demand for increased data return in order to return the same volume of data per unit of distance roved.

In addition to the sheer volume of data returned, the energy efficiency, or energy-per-bit that the landed asset must expend, of the data return link is a key parameter in terms of supporting data return from small, energy-constrained landers such as Beagle2 and Netlanders. These scout-class spacecraft, with limited mass, volume, and power, cannot communicate directly to Earth; instead, these mission concepts are enabled by energy efficient relay communications to an overhead Mars orbiter, which then handles the demanding "trunk-line" communications back to Earth.

A third challenge is the need for precision Mars-relative navigation in a variety of mission scenarios. Precision landing and aerocapture demand highly accurate approach navigation. The loss of the 1998 Mars Climate Orbiter underscored the desire for highly robust approach navigation utilizing a complementary suite of data types. Once on the surface, highly mobile rovers will utilize radio-based navigation to maintain overall position knowledge. Finally, Mars sample return will likely require on-orbit rendezvous of a Sample Return Orbiter with an orbiting sample canister launched into Mars orbit by a Mars Ascent Vehicle; accurate tracking and navigation of these elements will be required to support successful rendezvous.

In the remainder of this paper we will address each of these issues in turn and discuss how these challenges are being met in the overall program of Mars exploration. In particular, we will see how the unique capabilities of the G. Marconi telecommunications relay orbiter will play a key role in the overall program strategy.

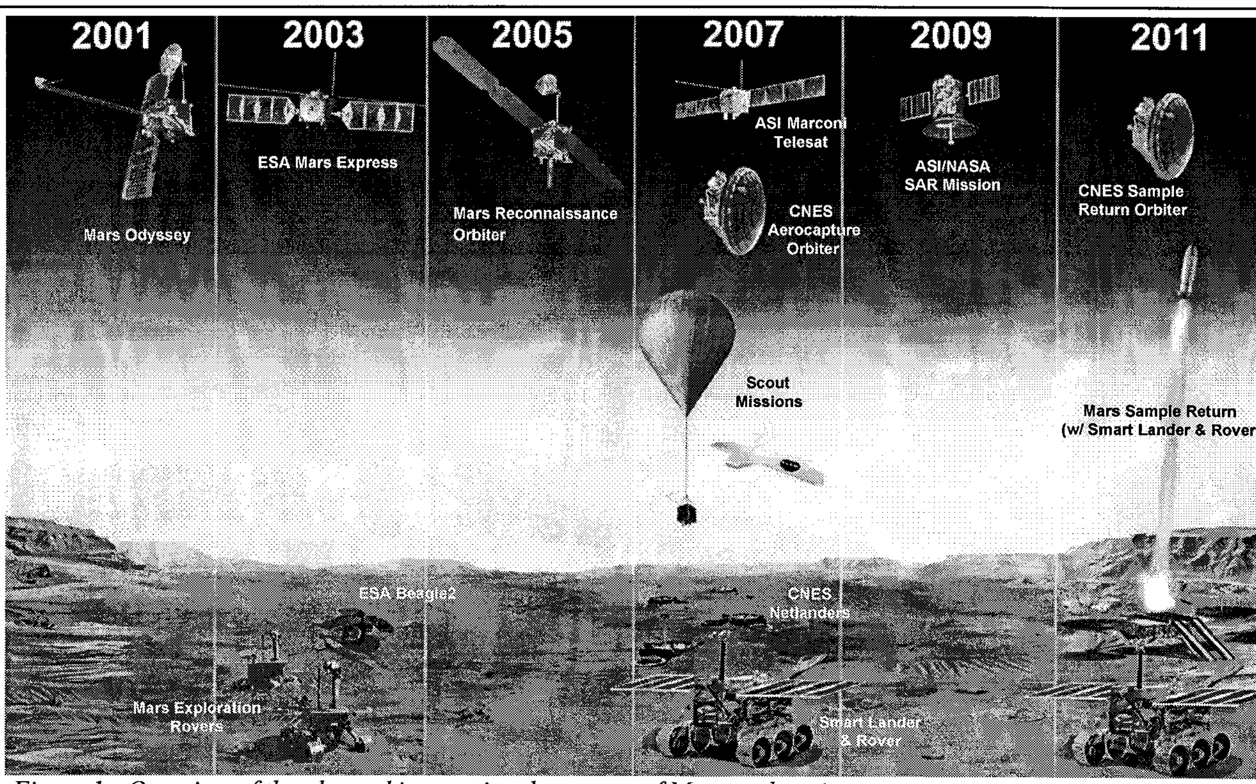

Figure 1: Overview of the planned international program of Mars exploration

Critical Event Communications

The key challenge of critical event communications is the need to establish a reliable communications link *at a given place* and *at a given epoch.* This requires that the receiving end of the link must be in view of the transmitting spacecraft during that spacecraft's critical event. Compounding the challenge of critical event communications is that in many cases (for instance, during EDL) spacecraft attitude and spacecraft dynamics are not well known *a priori.*

It is illustrative to look at the case of EDL communications for the 2003 Mars Exploration Rovers. Figure 2 depicts the January 4th, 2004 arrival geometry for MER-A, assuming a launch date of May 30, 2003. (A similar geometry exists for the MER-B arrival three weeks later on January 25th, 2004.) The landing site will be in view of Earth, and so a direct-to-Earth X-band link can be used to monitor the progress of the EDL sequence. However, because a very low-gain, wide beamwidth antenna must be used during EDL, due to the unpredictable attitude variations during the atmospheric descent, the resulting DTE link is extremely tenuous. Even using a 70m DSN antenna for reception, the signal is too weak to support standard coherent data modulation. Instead, MER will employ a "semaphore" strategy in which one of 256 subcarrier tones will be radiated and detected at Earth over a 10-sec integration period. The resulting M-ary Frequency Shift Keying (MFSK, M=256) effectively allows transmission of 8 bits of information over each 10-sec integration. As a result, only a few hundred bits of information can be transmitted during the entire six-minute descent. And it is expected that lander attitude variations, particularly after parachute and bridle deployment, will lead to intermittent dropouts of the X-band DTE link. Nonetheless, these data, coupled with the Doppler information of the received signal (which contains information on MER line-of-sight velocity changes) will provide important diagnostic information in the event of an anomaly during EDL.

However, to improve the robustness of the MER EDL critical event communications, the program has examined the possibility of providing UHF communications support from one of the three science orbiters that will be at Mars at the time of MER arrival: Mars Global Surveyor (MGS), which will be well beyond its original mission lifetime; Mars Odyssey, which will have arrived in 2001 and be well within its design lifetime, nearing completion of its first year of orbital science; and Mars Express, which will have just arrived on December 24th, 2003. All three of these orbiters are equipped with UHF relay communications systems.

Based on lifetime considerations, Odyssey would seem to be a natural choice. However, when we look at the problem of link availability at the position and epoch of the EDL event, we reach a different conclusion. As shown in Figure 2, the Odyssey spacecraft is in a 400 km sun-synchronous orbit with a local time of roughly 4-5 PM. This local time is driven by optimal geometry for the science instruments on board the spacecraft. In order to support EDL communications, it is necessary to ensure that the orbit plane passes over the EDL site, and that the spacecraft true anomaly, or position within that obit plane, is phased to pass over the EDL site at the correct time. Figure 3 shows the orbiter fuel costs, in DeltaV, for worst-case adjustments in the in-orbit phasing and the nodal plane. These costs scale inversely with the length of time over which the adjustment needs to be effected. The plot reveals that in-plane phasing adjustments can be made at relatively low cost, while changing the orbit plane is extremely costly. For instance, a 180 deg in-plane phasing adjustment can be made over a 100-day interval for less than 1 m/s, whereas a 90 deg plane change over that same time requires roughly 300 m/s of Delta V. For reference, the Odyssey spacecraft allocates less than 100 m/s for orbit adjustments and orbit maintenance over its mission lifetime.

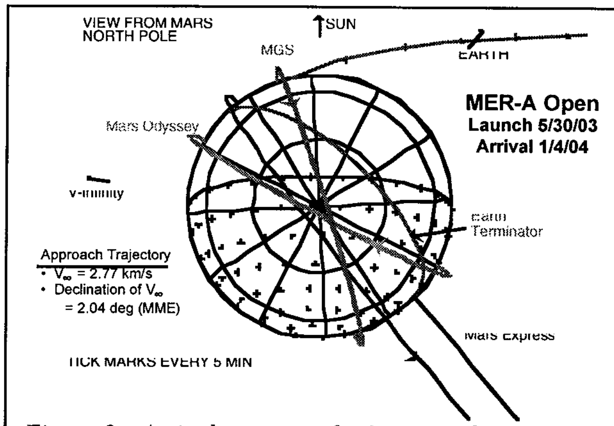

Figure 2: Arrival geometry for MER A, showing position of potential relay orbiters for EDL critical event communications support

In addition to the high fuel costs of orbital plane changes, such a strategy would significantly impact the Odyssey orbital science campaign due to local-time constraints of the Odyssey Gamma Ray Spectrometer instrument, and would also impact the overall spacecraft energy budget due to increased eclipse periods. For these reasons, Odyssey was ruled out as a relay asset for collecting EDL telemetry. Mars Express was also ruled out, largely due to the fact that it will have just arrived at Mars. Instead, the Mars Global Surveyor spacecraft will be utilized to collect EDL telemetry at UHF, augmenting the limited DTE X-band capability. MGS, in roughly a 1 PM local time orbit, is well-positioned to view the MER-A and MER-B EDL events. However, MGS will be well beyond its primary mission life, and a program of fuel conservation has been initiated to preserve MGS consumables through the two MER EDL missions.

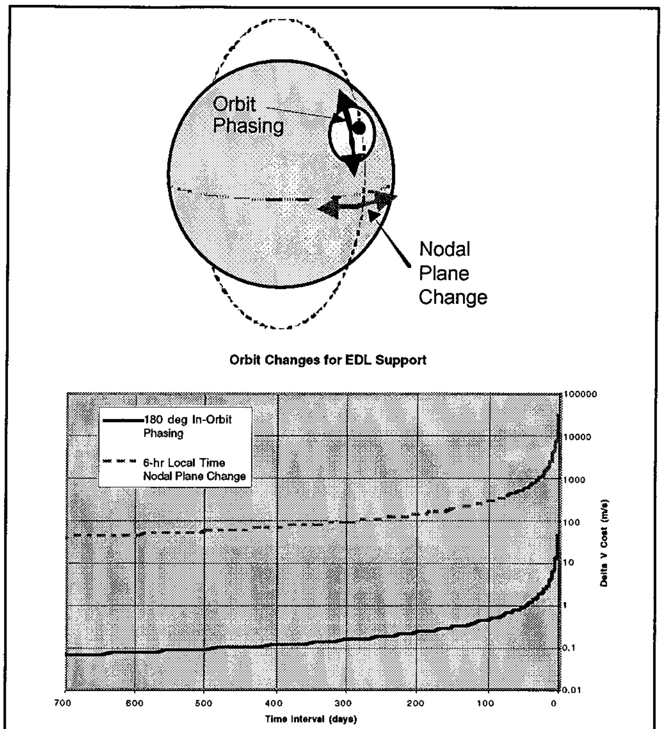

Figure 3: Delta-V costs for relay orbiter in-orbit phasing and nodal plane change orbit adjustments

All of this highlights the difficultly of using low-altitude science orbiters, with their limited ground footprint, to support critical event communications. Figure 4 quantifies the problem and shows how higher-altitude orbits can greatly improve the ability to support critical event communications over a much larger region of the planet. A natural reference frame in which to consider critical event communications support is defined by a sphere with coordinates of Mars latitude and Mars local time. A given sun-synchronous orbiter will have a fixed orientation (to first order) in this reference frame, and approach trajectories for EDL or MOI will similarly target a specific latitude and local time based on the Earth-Mars cruise trajectory.

The instantaneous footprint that can be viewed from the relay orbiter increases as one moves to higher altitudes. The footprint, measured as a fraction of the reference sphere that can be viewed instantaneously, is given by:

$$f_1 = \frac{1}{2}\left\{1-\cos\left(\frac{\pi}{2}-\theta_{el}-\arcsin\left[\left(\frac{r}{r+a}\right)\cos\theta_{el}\right]\right)\right\}$$

where

r = Mars radius
a = Orbiter altitude
θ_{el} = Elevation mask

At 400 km, only about 3% of the reference sphere is instantaneously visible, for a 10 deg elevation mask. One can also calculate the fraction of the sphere that can be viewed over a full orbit; EDL communications can be supported anywhere in this region simply with a low-cost in-plane orbit phasing adjustment. This quantity is given by:

$$f_2 = \sin\left(\frac{\pi}{2}-\theta_{el}-\arcsin\left[\left(\frac{r}{r+a}\right)\cos\theta_{el}\right]\right)$$

and corresponds to only 31% of the sphere for a 400 km orbit (again assuming a 10 deg elevation mask).

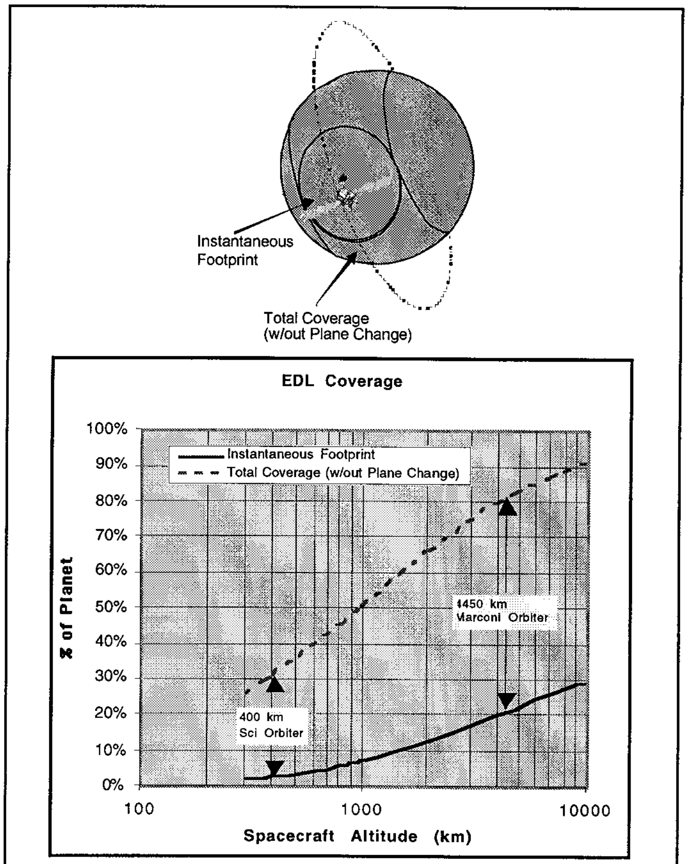

Figure 4: Comparison of EDL coverage statistics for 400 and 4250 km orbiters (Footprint calculated for 10 deg elevation mask)

The 2007 G. Marconi Telecommunications Orbiter, on the other hand, is currently baselining an orbit altitude of 4450 km, with a 130.2 deg inclination to maintain a sun-synchronous orbit. From this much higher orbit altitude, visibility of the latitude/local-time sphere is greatly improved: the instantaneous footprint corresponds to 21% of the planet, and 82% of the latitude/local-time sphere can be viewed over the orbit. Figure 5 contrasts the 400 and 4450 km orbits in another way by specifically outlining the regions of the latitude/local-time space that can be accessed from each orbit. The 400 km polar science orbit effectively only can cover roughly a two-hour range of local times near the equator. The 4450 km orbit, on the other hand, covers nearly the entire equatorial band, with just two small zones of exclusion, asymmetrically located in the northern and southern hemispheres due to the orbit inclination. It is evident that the Marconi orbit will provide a much more robust platform for establishing critical event communications for future missions.

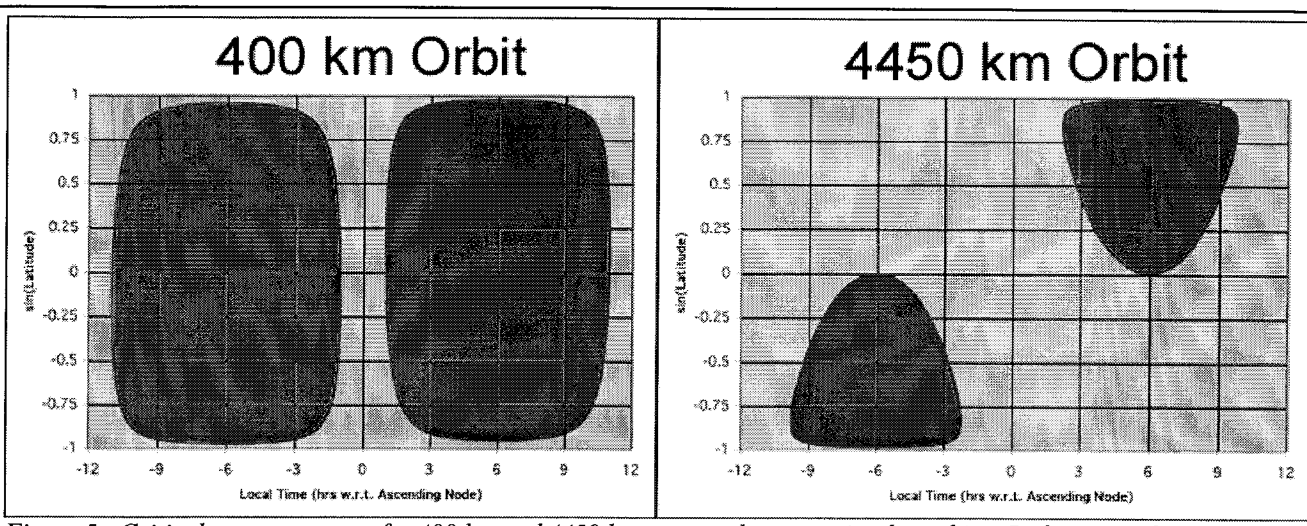

Figure 5: Critical event coverage for 400 km and 4450 km sun-synchronous circular orbits. Red areas indicate regions in a Mars-centered, sun-fixed reference frame, for which no critical event coverage can be supported; all points in the grey region can be viewed above 15 deg elevation with only an orbit phasing adjustment.

A particular challenge for Marconi will be the fact that both the 2007 Smart Lander EDL and the 2007 Premier Orbiter aerocapture represent important program feed forward flight validations for which critical event communications is desired. Since Marconi launches in the same 2007 launch opportunity, it is desired to bias the arrival date of Marconi sufficiently early to allow it to be on orbit and operational at the time of these two critical events. Collaborative mission design among these three missions will be required in order to understand the viability of this scenario and to quantify the spacecraft mass and launch vehicle implications of this early arrival.

In addition to the use of a high-altitude relay satellite, future missions will also consider what functionality they themselves can provide for critical event communications support. For instance, a lander mission with a direct entry could choose to upgrade its cruise stage to serve as a flyby relay asset just for EDL support. The advantage of this approach is that the cruise stage will naturally be directly overhead on its flyby as the lander enters the atmosphere.

Surface Relay Support

Next we turn to the challenge of telecommunications relay support to assets on the Martian surface. Larger landers and rovers, such as the 2003 MER rovers or the 2007 Smart Lander, have sufficient mass and power to deploy a directional high-gain X-band direct to Earth link. For instance, the MER rovers will carry a 28-cm gimbaled planar array antenna and a 15W X-band Solid State Power Amplifier, enabling data rates of 2-9 kbps into a DSN 70m antenna over the course of the surface mission. (The variation is due to the changing Earth-Mars distance.)

Lander/rover data return can be greatly increased by relaying data to a Mars-orbiting spacecraft, which can then transmit the lander data back to Earth. Because it is

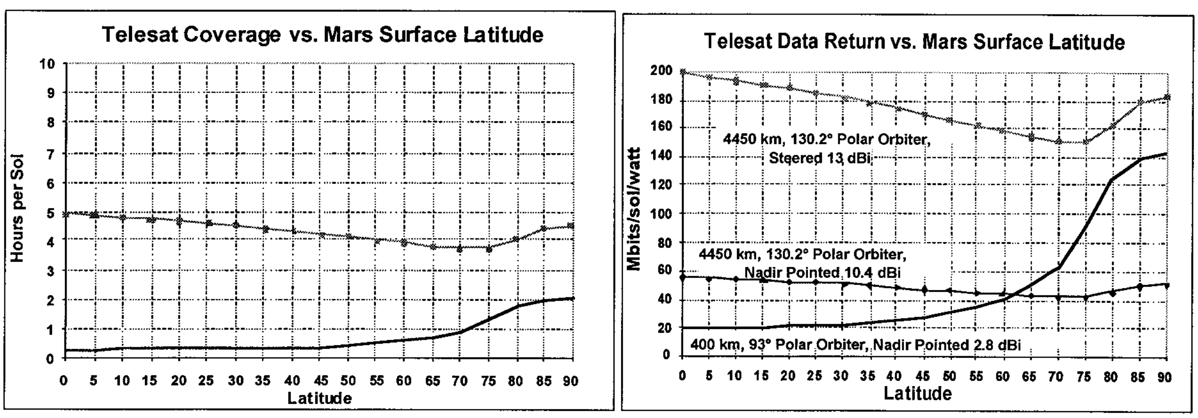

Figure 3: Coverage and data return for 400 km and 4450 km altitude telesat options

much cheaper to deliver antenna gain and RF power to Mars orbit, compared to the Martian surface, relay communication offers significant advantages relative to DTE communications from the Martian surface.

Currently, Mars proximity links are supported at UHF frequencies of 390-450 MHz, in accordance with the CCSDS Proximity-1 Link Protocol[1]. The choice of this frequency band is a compromise between link performance, which improves with increasing wavelength for the omni-to-omni communications links currently used in surface-to-orbiter proximity links, and component mass/volume, which increases with wavelength.

Previous studies have explored relay link performance in terms of key figures of merit such as data return per sol, energy per bit, contact time per sol, number of contacts per sol, and gap time between contacts[2,3]. The link availability metrics are simply functions of the relay orbit, while the data return and energy efficiency metrics are also a function of the relay orbiter's G/T, or ratio of relay orbiter antenna gain to system noise temperature.

Figure 6 illustrates some of these results, comparing proximity link coverage (in terms of hours/sol of contact time) and data return (in terms of data volume per sol per Watt of transmitted power for a surface asset with 0 dBi antenna gain). These results provide additional motivation for the selection of the 4450 km, 130.2 deg inclination as a baseline for the G. Marconi telesat. This orbit provides greatly increased contact time and relatively uniform coverage as a function of latitude. With the addition of a 10-15 dBi UHF medium gain antenna (MGA) to compensate for the increased space loss at this higher altitude, this orbit can still support high-rate, energy efficient proximity links, and the increased contact time translates into significantly increased data volume. Whereas a typical 400 km science orbiter with a low-gain UHF antenna provides roughly 20 Mb/sol/W for an equatorial surface user, a 4450-km orbiter with a steered 13 dBi UHF MGA can provide an order of magnitude greater data return per sol. In addition, the longer and more frequent passes will better support complex surface operations. Development of high-performance, low-mass orbiter spacecraft UHF MGAs in this 10-15 dBi regime are one of the highest-leverage technologies in terms of improving Mars proximity link performance.

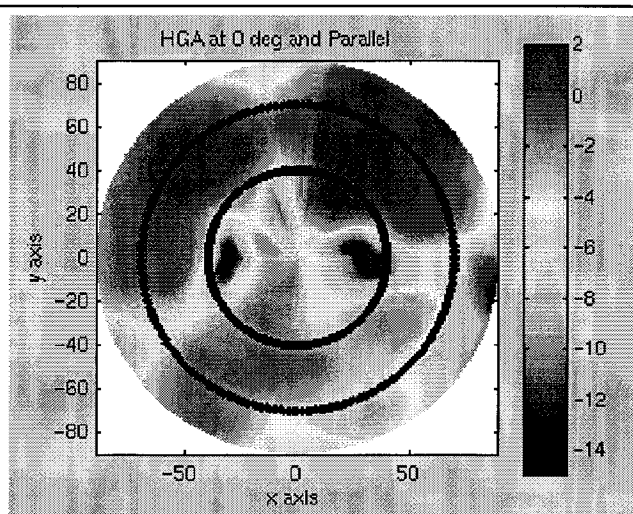

Figure 7: Measured antenna pattern for UHF monopole on MER

Recent experience with the Odyssey and MER missions provides several important lessons for future proximity link developments. First, antenna design and placement, and interactions between the relatively low-gain UHF antenna patterns and the spacecraft, can significantly affect proximity link performance. The antenna pattern of the quadrafilar helix antenna mounted on the nadir deck of the Odyssey spacecraft is significantly altered by interactions with the spacecraft body and the solar panels. Future orbiters will want to consider deploying these UHF antennas on a boom to provide a cleaner multipath environment and improved field-of-view. Boom deployment also reduces potential electromagnetic interference (EMI) concerns, and is a step towards a higher-gain, steerable proximity link antenna.

Antenna-spacecraft interactions are also an issue for rovers and landers. The Mars Exploration Rovers employ a simple monopole antenna. Figure 7 illustrates the pattern of the monopole, mounted on a mock-up of the MER structure. Deep nulls overhead and significant azimuthal asymmetry are evident in the measured pattern, due to interactions with the rover X-band DTE antenna and the PANCAM mast. In addition, the pattern varies depending on the orientation of the gimbaled X-band DTE antenna. These effects will lead to significant pass-to-pass variability in data throughput, depending on the azimuth at which the rover is pointing, geometry of the orbiter overpass, and the HGA orientation, and will result in increased complexity of surface operations. Future landers will want to consider improved antenna design and placement. For instance, a crossed dipole antenna on the rover would avoid the overhead nulls of the monopole and exhibit a much more azimuthally symmetric pattern, while also avoiding the monopole's 3 dB polarization loss.

Radio-Based Navigation

Radio frequency communications links also provide the opportunity to collect radio metric tracking observables which can provide important navigation information for a wide range Mars mission scenarios. Three particular scenarios of interest are: approach navigation, surface navigation, and in-orbit rendezvous.

Approach Navigation: The ability to target a specific site on the Martian surface, selected based on orbital remote sensing, requires the ability to land with a landing error ellipse smaller than the roving range of the landed asset. The 2007 Smart Lander will likely set a target of under 10 km uncertainty for its landing precision. Meeting this will require a combination of precision approach navigation, with arrival B-plane uncertainties of 1-2 km, combined with active aeromaneuvering during entry. Current DSN range and Doppler tracking can only provide arrival B-plane uncertainties of order 10 km. Several techniques are being investigated to reduce this to the 1-2 km level. Delta-Differenced One-way Range (Delta-DOR) observations provide extremely accurate plane-of-sky position determinations by measuring the difference in arrival times of the spacecraft signal at two separate DSN complexes. By differencing this spacecraft measurement with a similar measurement for an angularly close quasar, and by modeling the orientation of the baseline between the two DSN complexes, the spacecraft is tied into the inertial quasar reference frame. Current Delta-DOR observations of the MGS and Odyssey spacecraft suggest that angular accuracies of better than 10 nrad, or 1.5 km at maximum Earth-Mars distance, should be achievable.

A second proposed radio-based technique would establish an X-band (8.4 GHz) link between a Mars-approaching spacecraft and an orbiter already at Mars. The orbiter would receive the approach spacecraft's signal and measure its Doppler shift. If both spacecraft carry ultra-stable oscillators with stability of order 10^{-12} these one-way Doppler measurements can tie the approach spacecraft directly to the Mars reference frame with an accuracy on the order of 1 km. An operational consideration for this technique is that the two spacecraft need to point their X-band high-gain antennas at each other, off of Earth-point. Also, the link typically cannot be established until the final week or two of approach, depending on the EIRP of the approach spacecraft's X-band transmission and G/T of the orbiter's X-band receive system. In the final hours prior to entry, a two-way UHF link can be established between the two spacecraft, providing late, sub-km entry knowledge.

An alternative to radio-based techniques is to carry an optical camera onboard the approach spacecraft and use imaging of the Martian moons Phobos and Diemos, against the background of known star positions, to establish the incoming trajectory. Analysis suggests that this technique can also yield arrival accuracies of 1-2 km.

Missions in the 2007 time frame will consider combinations of these approach navigation data types to assure a robust, high-accuracy approach trajectory.

Surface Navigation: Once on the surface, two-way Doppler observations can be collected as a byproduct of UHF relay communications passes. Surface positions of 10-30 m can be obtained with two or more UHF passes. Obtaining this accuracy requires good orbit determination for the relay orbiter, and accurate time-tagging of the orbiter Doppler measurements relative to UTC. (The observed Doppler profile over a pass effectively ties the lander location to the orbiter's orbit; a time-tag uncertainty effectively "shifts" the entire data arc along the orbiter trajectory by an amount equal to the product of the orbital velocity times the Doppler time-tag error.)

Radio-based surface positioning of this kind can serve as a complementary navigation data type to direct rover image data in much the same way as a hiker on Earth uses a GPS receiver to complement visual cues and landmark tracking. In addition, a variant of this orbiter-lander UHF Doppler tracking, with the addition of a coherent second frequency for calibration of the Martian ionosphere, will be used to perform the Netlander NEIGE experiment, measuring sub-meter variations in the rotation of Mars due to a variety of geodetic effects[4].

In-Orbit Rendezvous: Rendezvous and retrieval of an in-orbit Mars Orbiting Sample (OS) will require accurate determination of the OS trajectory and collaborative navigation of the Sample Return Orbiter relative to the OS. A variety of sensor suites are under consideration at this time for supporting OS tracking and orbit determination. First, it is likely that the Mars Ascent Vehicle (MAV) that launches the OS will be instrumented with a radio system to transmit engineering telemetry during this first launch of a spacecraft from the surface of another planet. These transmissions would be received by an overhead relay orbiter, and could also be received by a rover positioned a safe distance away from the MAV launch site. In addition to the engineering telemetry, the received Doppler signal will provide information on the ascent vehicle trajectory and initial OS orbit.

Several approaches can be used to track the OS after launch. If the OS is equipped with an active radio beacon, Doppler tracking of the radio signal by on-orbit Mars relay spacecraft can provide OS orbit knowledge, with an accuracy largely determined by the stability of the OS oscillator. Preliminary covariance analysis suggests that with an OS oscillator stability of 10^{-8} over 60 s, the OS orbit can be determined to an accuracy of under 10 km. If the OS can coherently transpond a signal received from the relay orbiter, the orbit determination improves to well under 1 km.

Another approach under consideration would utilize an array of antennas on the Sample Return Orbiter to measure the angular direction of the OS relative to the orbiter antenna array. (The measurement is a small-scale versions of Delta-DOR, measuring the difference in arrival times of the OS radio signal at the various orbiter antennas.)

Finally, studies are underway of passive imaging systems, which simply detect the sunlit OS against the stellar background. It is likely that a robust approach to OS rendezvous will utilize a combination of two or more of these approaches.

Summary

The coming decade of Mars exploration will demand significant new telecommunications and navigation capabilities. The feed-forward coupling of many of the missions in the program queue make is essential that we can capture engineering telemetry during critical mission events such as Entry, Descent, and Landing. Once on the surface, energy efficient relay communications will significantly increase data return relative to direct-to-Earth links. For both critical event communications and surface relay support, the higher altitude under consideration for the 2007 G. Marconi telecommunications orbiter results in significantly improved capability relative to low-altitude science orbiters. Finally, radio metric tracking observables generated from these same communications links offer the potential for high-accuracy Mars-relative position determination for a variety of mission scenarios.

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Appendix: Telecommunications Characteristics of Mars Mission Set

Orbiters	Agency	Launch Date	Lifetime On-orbit	Orbit	Deep Space Link			Proximity Link		
					Band	Antenna	Tx Power	Band	Ant Gain	Tx Power
MGS	NASA	1996	7 yrs (1)	400 km, i=93 deg ~1 PM LMST	X/X	1.5 m	25 W	UHF	Omni	10 W
Nozomi	ISAS	1998	2 yrs		X/X	1.6m	6 W	n/a		
Odyssey	NASA	2001	4 yrs	400 km, i=93 deg ~5 PM LMST	X/X	1.3 m	15 W	UHF	Omni	10 W
Mars Express	ESA	2003	2 yrs	250 x 11,588 km, i=86 deg	X/X	1.8 m		UHF	6 dBi (TBC)	5 W (TBC)
MRO	NASA	2005	5 yrs	400 km, i=93 deg ~3 PM LMST	X/X (Ka?)	2.5 m	100 W	UHF, X	Omni (UHF) Omni/HGA (X)	10 W
G. Marconi Telesat	ASI/NASA	2007	6 yrs (1)	4450 km, i=130 deg	X/Ka	TBD	TBD	UHF, X	>10 dBi (UHF) Omni/HGA (X)	10 W
Premier	CNES	2007	2+ yrs (2)	TBD	X/X	0.8 m		UHF	Omni	10 W
Radar Science Orbiter	ASI/NASA	2009	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Mars Sample Return Orbiter	CNES	2011	TBD	500 x 500 km, i=45 deg	TBD	TBD	TBD	TBD	TBD	TBD

(1) Proposed E2 mission provides support through Sep'04
(2) Baseline 2 yrs on-orbit relay support to Netlanders; extended mission option not yet selected

In Situ S/C	Agency	Launch Date	Lifetime	Location	Deep Space Link			Proximity Link		
					Band	Antenna	Tx Power	Band	Ant Gain	Tx Power
MER-A, MER-B	NASA	2003	90 days	-15 - +10 deg LAT	X/X	30 cm	15 W	UHF	Omni	10 W
Beagle	ESA/DERA	2003	180 days	0 - +10 deg LAT	n/a			UHF	Omni	5 W
NASA Smart Lander	NASA	2003	TBD	TBD	X/X	TBD	TBD	UHF	Omni	10 W
Netlanders (4 landers)	CNES	2007	1 Mars yr	TBD	n/a			UHF (3)	Omni	6.5 W
NASA Scout (2)	NASA	2007	TBD	TBD	TBD			TBD		
Mars Sample Return Lander (1)	NASA	2011	TBD	TBD	TBD			TBD		
NASA Scout (2)	NASA	2011	TBD	TBD	TBD			TBD		

(1) Includes Mars Ascent Vehicle and Orbiting Sample Canister, which plan to utilize UHF transmission for tracking
(2) Competed scout mission could be lander, aerobot, or orbiter; could be multi-s/c
(3) Also includes S- or X-band coherent carrier surfact-to-orbiter link to support NEIGE radio science exp